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Restoration of hard mast species for wildlife in Missouri using precocious flowering oak in the Missouri River floodplain, USA

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Abstract

Increased planting of hard mast oak species in the Lower Missouri River floodplain is critical as natural regeneration of oak along the Upper Mississippi and Lower Missouri Rivers has been limited following major flood events in 1993 and 1995. Traditional planting methods have limited success due to frequent flood events, competition from faster growing vegetation and white-tailed deer herbivory. Results of early growth response of swamp white oak (*Quercus bicolor* Willd.) seedlings in relation to initial acorn mass and size, and early rapid shoot growth for seedlings produced by containerized root production method (RPM™), are presented. Containerized RPM™ seedlings grown in the greenhouse under optimal conditions demonstrate that seed size had no discernable impact on first-year root or shoot size. Seedling survival for the first two years and acorn production for the first three years after outplanting are presented, comparing use of containerized RPM™ swamp white oak seedlings to nursery stock. Flood tolerant precocious RPM™ oak seedlings in the floodplain provide a source of food for acorn-consuming wildlife ten to fifteen years sooner than oaks originating from natural regeneration, direct seeding or traditional bare root planting. Compared to bare root nursery stock that produced no acorns, some RPM™ swamp white oak seedlings averaged 4.3, 5.2, and 6.3 acorns/seedling in the first three years after fall outplanting.

Introduction

Floodplain forests

Forested floodplain habitats, once abundant in the continental United States, have been reduced by 70 to 90 percent of their pre-European extent (Bragg and Tatschl 1977; Knutson and Klaas 1995) due largely to land clearing for agriculture and the construction of dams and levees to protect valuable cropland and aid navigation. Much of the loss of hard mast species such as the oaks occurred in the first wave of land clearing because they were most common on the elevated, better drained soils, and hence the prime agricultural lands in the floodplains. River channelization and improvements for flood protection have allowed for more of the floodplain to be converted to agriculture, and have drastically altered river hydrology resulting in increases in the frequency and duration of high intensity floods. Changes in flood regimes in the Missouri and Mississippi River systems have adversely affected tree growth, increased mortality in the less flood tolerant species such as pin oak (*Quercus palustris* Muenchh.), and caused successional shifts in composition to more flood tolerant species in the remnant floodplain forests (Johnson et al. 1974). The abundance of species such as swamp white oak (*Quercus bicolor* Willd.), pin oak, black walnut (*Juglans nigra* L.), pecan (*Carya illinoensis* (Wangenh.) K. Koch), and shellbark hickory (*C. laciniosa* (Michx.f.) Loud.) has been greatly reduced, as has the areal extent of cottonwood (*Populus deltoides* Bartr. ex Marsh.), silver maple (*Acer saccharinum* L.) and sycamore (*Platanus occidentalis* L.) forests (Bragg and Tatschl 1977; Yin et al. 1997). The loss of floodplain forests and in particular hard mast species is of concern to wildlife biologists, foresters and private landowners. Mast refers to food for wildlife and hard mast refers to seed with a hard shell from species such as oak, hickory and pecan, in contrast, soft mast refers to seed with a fleshy covering such as persimmon, dogwood and black gum.

Flood and environmental protection benefits of floodplain forests

Woody vegetation growing in the floodplain increases streambank stability (Geyer et al. 2000), protects levees, and reduces negative impacts of flooding caused by scouring, deposition and infrastructure damage (Dwyer et al. 1997). Levee failure was especially prevalent along the Lower Missouri River during the 1993 flood, resulting in millions of dollars in damage to agricultural crops and cropland (U.S. Army Corps of Engineers 1996). A study conducted by Dwyer et al. (1997) along a 63-kilometer stretch of the Lower Missouri River found that as the width of the woody corridor between the river bank and the primary levee increased, the damage in both numbers and size of levee failures decreased during the flood of 1993. They also found that 90 meters was the minimum width necessary for a woody corridor to be effective in reducing levee failures.

Beyond flood protection, floodplain forests can increase groundwater storage, increase soil productivity and reduce nutrient run-off by absorbing, filtering and transforming excess fertilizer applied to adjacent cropland (Sparks 1995).

Value of floodplain forests for wildlife habitat

Rivers and their floodplains are among the most highly productive ecosystems in the world providing habitat for a wide diversity of wildlife. In the United States, the Missouri and Mississippi Rivers serve as major corridors for migrating birds (Sparks 1995), as well as habitat for many year-round resident wildlife species. Floodplain forests provide a diversity of habitat for many forest dwelling bird species, mammals, amphibians and reptiles (Dwyer et al. 1997; Sparks 1995; Yin et al. 1997). In landscapes dominated by agricultural production, riparian forests may be the only forest habitat remaining for wildlife. Some species of wildlife use the riparian zone to fulfill all their life requirements, while others use it only a portion of the time for critical activities such as feeding, breeding, or as escape cover. Hirsch and Segelquist (1978) found that 90 percent of the white-tailed deer in Louisiana lived in bottomlands even though that type of habitat only made up 50 percent of the potential deer range in the state.

Acorns are relatively high in fat and carbohydrates and are good sources of protein, vitamins, calcium and phosphorus (Goodrum et al. 1971). Numerous wildlife species require hard mast for a food source; waterfowl using floodplain forests for wintering areas depend on hardwood mast for the bulk of their diets (Hirsch and Segelquist 1978). Some species of wildlife (e.g., squirrel and turkey) rely on acorns much of the year (e.g., Christisen and Korschgen 1955), while others are more seasonal in their consumption.

The quantity of acorns produced in a season can have an effect on wildlife populations and indirectly on how wildlife impact other vegetation through browsing and foraging. Wildlife populations can effect acorn production and in years of low to moderate acorn production, wildlife can consume nearly the whole crop. Goodrum et al. (1971) estimated that 100 kilograms of acorns per hectare are required to satisfy the requirements of five species of wildlife (white-tailed deer, gray squirrel, fox squirrel, turkey and bobwhite quail) for 300 days. Approximately nine white oaks, 40 centimeters in diameter, would be required to produce this amount of acorns (Goodrum et al. 1971).

Floodplain restoration for wildlife

The Great Flood of 1993 degraded over 325,000 hectares of cropland in the Lower Missouri River floodplain by depositing sand and scouring fields. Thousands of hectares of flood-damaged lands were purchased by state and federal agencies from willing sellers since 1993. Managers are interested in reforesting many of these floodplain properties and ensuring that the forests have the capacity to produce hard mast.

Light-seeded windblown species are naturally adapted to old-field invasion, whereas heavy-seeded mast species, such as oak and pecan, require a nearby seed source (Newling 1990). Along the Missouri and Mississippi Rivers, the regeneration of light-seeded, pioneer tree species such as cottonwood, willow (*Salix* spp.) and silver maple has been so successful that heavy-seeded, mast-producing species important for wildlife have difficulty regenerating. Hard mast species have had difficulty becoming established due to intense competition from pioneer tree species and lush growth of herbaceous species, their inherent slow juvenile growth, flooding and deer herbivory (Buckley et al. 1998).

Artificial regeneration of hard mast species is needed where there is a lack of a local seed source (Newling 1990). Artificial regeneration has traditionally involved sowing seed or planting bare root seedlings. Attempts to establish oak and other nut species in bottomland fields have often failed despite our best knowledge and efforts. Traditional methods of planting bare root seedlings or direct seeding of oak in bottomlands has not always been successful, even with annual weed control during the establishment period. These methods have not reliably produced adequately stocked forests. For example, in a survey of 4-year-old Wetland Reserve Program plantings in the Mississippi River floodplain, Schweitzer and Stanturf (1997) found that only 9% of the total reforested land in 13 Mississippi counties met the Natural Resources Conservation Service requirement for at least 310 hard mast stems per hectare in 3-year-old stands. An alternative to traditional regeneration practices in floodplains is the use of large containerized (e.g., 11.4 to 18.9 liters) seedlings produced by a new nursery cultural system known as the root production method (RPM™ is a registered trademark of Forrest Keeling Nursery which reserves the rights to use this name).

Root Production Method™ for floodplain restoration

The RPM™ process used to produce large container seedlings is described in the methods section. Seedlings grown by this method can attain heights greater than 1.5 meters in one to two years, have basal diameters approaching 2.5 centimeters, and have root systems that are 3 to 7 times the dry mass and 4 to 9 times the volume of 1-0 bare root seedlings (Shaw et al. 2002).

In the Upper Mississippi and Lower Missouri River floodplains, RPM™ seedlings have considerable advantages over traditional bare root nursery stock including (1) improved growth and survival, (2) large root systems that do not experience the damage and transplant shock of bare root seedlings, (3) crowns more likely to be above growing season floods, (4) a terminal shoot above deer browse height (i.e., $>$ 1.5 meters), (5) large basal stem diameter ($\geq$ 1.5 centimeters) and (6) precocious flowering and mast production.

While we do not fully understand early fruiting in plants grown by the RPM™ process, it is not uncommon and occurs in a variety of tree, shrub and herbaceous species. Early acorn production in oaks is unusual considering that naturally and artificially regenerated oaks normally require 15 to 35 years to produce acorns (Schopmeyer 1974). Questions concerning precocious mast production in oak prompted this research to be undertaken along with a lack of research on the RPM™ process.

Purpose and objectives

The purposes of the research were to establish base line data on early morphological characteristics of bottomland swamp white oak that may lead to precocious flowering in seedlings produced by the RPM™ process, and to monitor outplantings for early acorn production. Specific objectives accomplished through two related studies were twofold: 1) to determine the effect of acorn size and mass, and early rapid shoot growth on morphological characteristics of one-year-old seedlings propagated under the RPM™ system; and 2) to compare RPM™ and nursery stock swamp white oak seedling survival and acorn production after two and three years in the field, respectively.

Materials and methods

Objective 1

In the first study acorns were collected in the fall of 1999 from randomly sampled *Quercus bicolor* (Willd.) trees in Saline County, Illinois. In the normal RPM™ process, acorns are graded by mass and diameter. Only the heaviest and largest set of acorns are stratified over the winter. In February, acorns are germinated in heated greenhouses in mesh-bottomed trays that allow for air pruning of the roots. Following the first shoot flush, seedlings are graded by rapid initial shoot growth and only the fastest growing seedlings (approximately the tallest 50 percent of germinates) continue in the RPM™ process. After a series of transplants into increasingly larger bottomless containers, seedlings are finally potted in shallow 11.4 or 18.9 liter pots with a growth medium of composted rice hulls, pine bark and sand that has 35 percent air space. Seedlings are then placed outside for the remainder of the growing season. Typical RPM™ seedlings attain heights of 1.5m or taller after 210 days of growth and they develop dense, fibrous root systems high on the root collar.

For this study, acorns were grown into seedlings by the RPM™ process with the following important exceptions: as acorns and seedlings were graded, all seed and plant materials were separated and retained in their respective size classes instead of being discarded (i.e., both large and small seed, heavy and light seed and rapid and slow initial shoot growth). This resulted in eight treatments that represent all combinations of acorn mass (heavy or light), acorn size (large or small) and shoot growth (rapid or not). Due to poor germination there were fewer than expected seedlings for some treatments and this required use of two experimental designs. A 3×3 balanced lattice square design with four replications, where each observation was from one seedling, was used to examine all eight treatments. A 4×4 balanced Latin square design was used with only the four initial rapid shoot growth treatments. Each block within each design contained three seedlings from which a statistical mean was derived to obtain one observation.

At the end of the growing season, all seedlings were destructively sampled and measurements were taken on seedling characteristics. Variables measured included root collar diameter (measured 2.5 cm above the root collar), height, root volume, root, shoot and total dry mass and number of shoot flushes. Root volume was measured by the displacement method described by Böhm (1979). Seedling mass was recorded after seedlings were oven dried and weighed on a top loading balance. SAS Version 8.2 was used to conduct the analysis of variance, to test hypotheses relating acorn mass, acorn size and initial shoot growth to first-year RPM™ seedling morphology, and to determine least significant differences (LSD) between treatment means.

Objective 2

For purposes of the second study, four 16.2-hectare square (402 m^2) blocks were equally divided between two conservation areas managed by the Missouri Department of Conservation: Smokey Waters (Sec. 5, T 44 N, R 9 W and Sec. 1, T 44 N, R 10 W; Cole County) and Plowboy Bend (Sections 24, 25, T 47 N, R 14 W; Moniteau County). Soils were mapped as Haynie Silt Loam (coarse-silty, mixed, superactive, calcareous, mesic Mollic Udifluvents) and Leta Silty Clay (clayey over loamy, smectitic, mesic Fluvaquentic Hapudolls) at Smokey Waters, and Sarpy Fine Sand (mixed, mesic Typic Udipsamments) at Plowboy Bend. Each planted area was randomly assigned a cover crop treatment: redtop (*Agrostis alba* L.) grass cover crop, or no cover crop. Rows were spaced 9.1 meters apart. Stock types included 1-0 bare root, and two classes of RPM™ seedlings. Species included pin oak (*Quercus palustris* Muenchh.) and swamp white oak (*Q. bicolor* Willd.). In this paper, only swamp white oak data are presented. Seedlings were planted on a spacing of 9.1 m within each row (9.1 m×9.1 m spacing = 120 trees/ha). Within a cover crop treatment (16.2-hectare block), stock type and species treatments were replicated 4 times. Additional trees were planted at field edges to reforest the entire 16.2 ha.

Approximately 1,200 seedlings of each stock type were planted in randomly located 30-tree plots. RPM™ trees were planted in November of 1999 and 1-0 bare root seedlings were planted in the spring of 2000. At the time of planting, a slow release fertilizer (33-3-6) was applied to the ground surface about each seedling at an approximate rate of 30 g per tree. A 1.2×1.2 meter woven plastic weed mat was placed around each seedling in the spring. Additional detail regarding materials and methods are found in Dey et al. (2003).

Initial total height and basal stem diameter (2.5 centimeters above ground) were measured on all seedlings before the 2000 growing season. Seedling heights and basal diameters were remeasured at the end of the first and second growing season (winters 2000/2001, 2001/2002). In mid-August 2000, 2001 and 2002, a survey of acorn production was conducted on all RPM™ swamp white oak treatments.

Results and discussion

Effect of early rapid shoot growth, acorn mass and acorn size on seedling characteristics

Early rapid shoot growth was not found to be significantly related to first-year seedling morphology, therefore further analysis focused on acorn mass and size treatments. Seedlings from the light-small (LS) treatment had greater height, root volume, shoot dry weight and root dry weight than seedlings from any other acorn mass-size treatment combination, however these differences were not significant based on analysis of least significant differences (Figure 1). Average root to shoot ratios were between 1.2 and 1.3 and were not significantly different among treatments.

Results found here are not consistent with most research on the acorn effects on seedling characteristics. Researchers have found that seed mass is positively correlated with early seedling growth (Rice et al. 1993; Bonfil 1998). Long and Jones (1996) also found no effect of acorn mass and size on seedling characteristics, but suggest that poor control over acorn moisture content (in their study and others) and genotypic variation on seed size could have influenced their results. Studies that involved the removal of a portion of the acorn prior to sowing, or removal of the cotyledons shortly after germination, found that seedling growth was more affected by poor soil nutrition than by loss of acorn mass (Sonesson 1994; Anderson and Frost 1996). Furthermore, it has been speculated that acorn size may be more important in attracting wildlife for seed dispersal than for first-year growth (Anderson and Frost 1996).

Conflicting results may also be due to differences in propagation methods. Traditionally seedlings have been grown in seedbeds as bare-rooted nursery stock under less than ideal conditions for rapid growth. Containerized RPM™ seedlings grown in the greenhouse under optimal growing conditions are under no stress and are relatively free from competition compared to seedlings grown in the wild or in nursery beds. Larger seeds may have advantages over smaller seeds if both are grown in competition (Bonfil 1998), but under low stress and competition-free environments, little appears to be gained from larger seeds.

RPM™ seedlings grown in the absence of stress or competition have an extremely dense, fibrous root system with numerous lateral roots. These root systems provide a greater surface area for the absorption and utilization of oxygen, water and nutrients than bare-rooted seedlings. Optimal growing conditions under the RPM™ system, coupled with a dense, fibrous root system appear to minimize the effect of acorn mass on oak seedlings after one growing season.

Survival and acorn production by stock type

Oak survival was initially high (e.g., $> 95\%$) for both bare root and RPM™ swamp white oak seedlings planted in a former agricultural cropfield in the Missouri River floodplain (Dey et al. 2003). However, bare root seedling survival dropped to 77.4% by the end of year two while RPM™ trees remained above 95%. In contrast to 1-0 bare root swamp white oak seedlings, RPM™ seedlings 18 to 24 months old at time of planting produced acorns in each of the first three years following outplanting (Table 1). For the RPM™ trees that produced acorns during the first three years in the field, average acorn production ranged from 4.3 ± 4.4, 5.2 ± 9.2 to 6.3 ± 7.5 acorns/tree respectively. Individual trees were able to produce as many as 45 acorns. The probability of a RPM™ swamp white oak seedling producing at least one sound acorn in the first year after planting was significantly ($p < 0.001$) related to initial basal diameter and height of the seedling (Figure 2). Acorn production was more likely to occur in the first year for large diameter (> 12.7 mm), tall (> 1.5 m) RPM™ seedlings. Consistent, early production of acorns is surprising considering that open-grown oaks do not begin producing seed until they are 15 to 35 years old.

Conclusions

Bottomland reforestation with RPM™ seedlings has been very successful, with little or no mortality and acorn production in the first through third year after outplanting (Dey et al. 2003). Precocious flowering and fruiting provides a seed source for natural regeneration as well as food for acorn consuming wildlife much earlier than traditional oak plantings. The results presented in these studies establish base-line data for future studies that investigate precocious acorn production in RPM™ oak seedlings. These studies also provided conclusive evidence that both high survival and consistent early acorn production are achievable under floodplain field conditions.

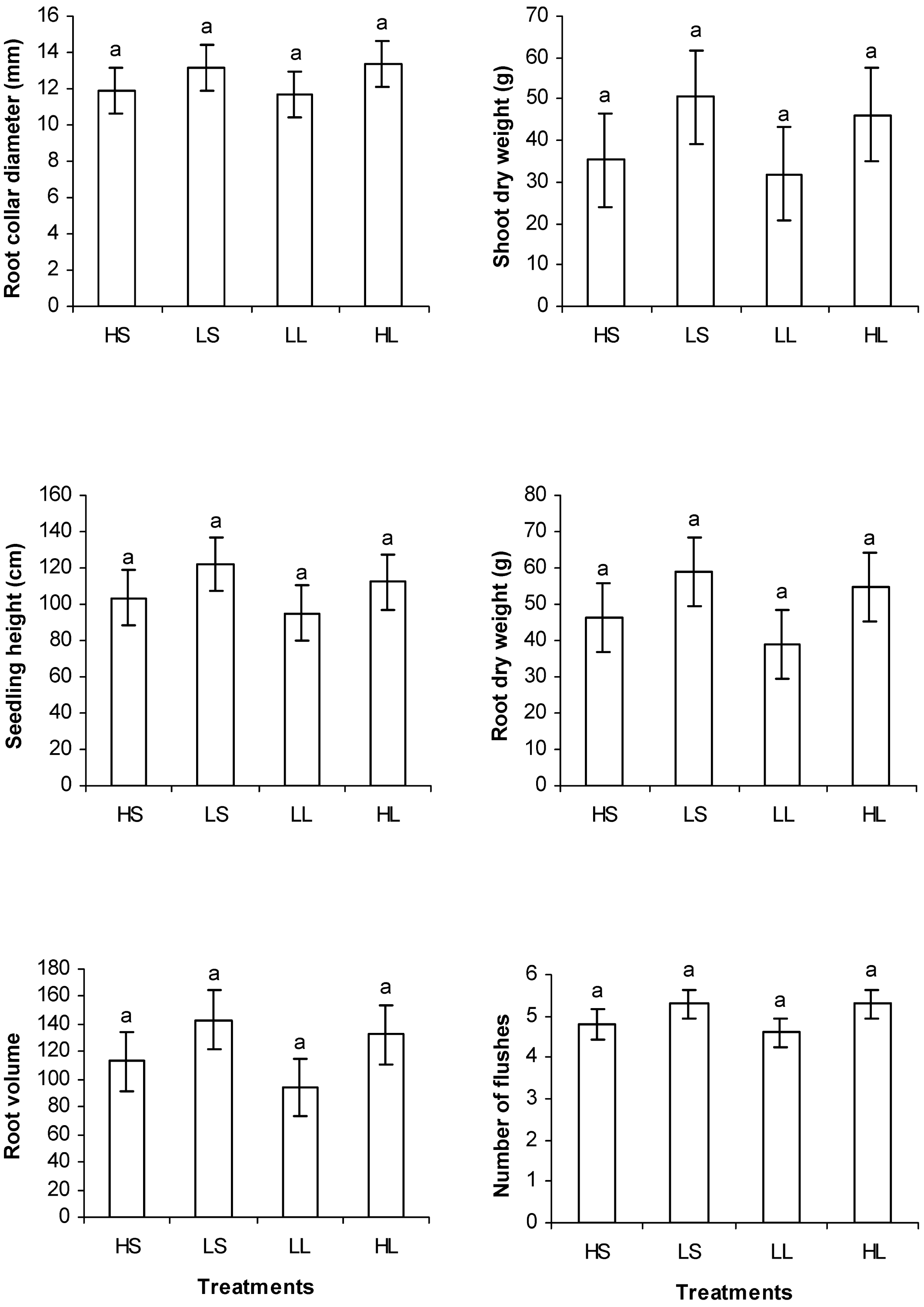

Figure 1. The effect of acorn mass and size on first-year morphology of RPM™ container-grown seedlings of swamp white oak (*Quercus bicolor*) in the Lower Missouri River floodplain, USA; Treatments: HS=heavy-small, HL=heavy-large, LL=light-large, LS=light-small. Means +/- standard error. Treatments with the same letter above the bar do not differ significantly at the alpha = .05 level.

Table 1. Table 1. Acorn production by two stock types of swamp white oak (Quercus bicolor) during three years after planting in the Lower Missouri River floodplain, USA

	Year one production			Year two production			Year three production		
Stock type	Number of seedlings with acorns	Mean # acorns per seedling	Range	Number of seedlings with acorns	Mean # acorns per seedling	Range	Number of seedlings with acorns	Mean # acorns per seedling	Range
RPM™	86	4.3 ± 4.4	1-21	29	5.2 ± 9.2	1-45	70	6.3 ± 7.5	1-42
Bare root	0	0	0	0	0	0	0	0	0

Means +/- standard error. Data was collected from four 16.2-hactare square blocks equally divided between two conservation areas in central Missouri managed by the Missouri Department of Conservation: Smokey Waters (Sec. 5, T 44 N, R 9 W and Sec. 1, T 44 N, R 10 W; Cole County) and Plowboy Bend (Sections 24, 25, T 47 N, R 14 W; Moniteau County). Each planted area was randomly assigned a cover crop treatment: redtop grass or no cover crop. Stock types included 1-0 bare root, outplanted in the spring of 2000, and two classes of RPM™ seedlings, outplanted in the fall of 1999. Seedlings were planted at 9.1 x 9.1 meter spacing totaling 120 trees/ha. Additional trees were planted at field edge to reforest the entire 16.2 ha. Approximately 1,200 seedlings of each stock type were planted in randomly located 30-tree plots.

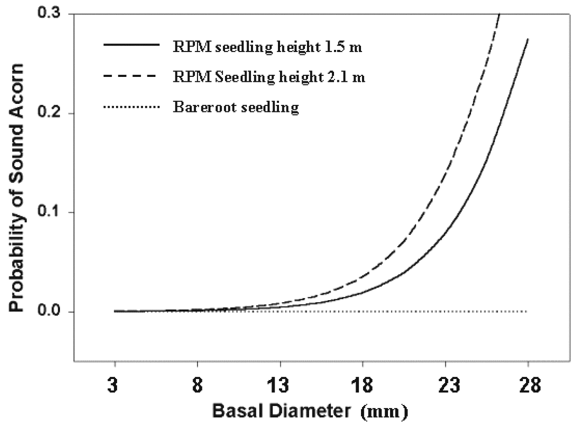

Figure 2. The probability of producing at least one sound acorn during the first year in relation to initial basal diameter and height of swamp white oak (*Quercus bicolor*) RPM™ and 1-0 bare root seedlings) in the Lower Missouri River floodplain, USA. [Prob = $(1 + \exp(-(10.6662 + 0.2914*BD + 1.0211*HT)))^{-1}$, where, Prob = probability of producing at least one sound acorn in the first year; BD = initial basal diameter (mm), measured 2.5 cm above the ground, and; HT = initial height (m)]. Source: Adapted from Dey et al. 2003.

Because acorns and other nuts are so valuable to wildlife, restoring hard mast production in floodplain forests would improve the quality of wildlife habitat. Additionally, restoration with improved mast producing selections would dramatically increase per hectare acorn production. Waterfowl migrating through the Missouri River flyway will be positively impacted in future years by successful re-establishment of a hard mast component to floodplain forests.

An alternative to an oak monoculture for bottomland reforestation is implementing an agroforestry design by planting mast-producing RPM™ seedlings (i.e., oak and pecan) at a slightly wider spacing and interplanting early successional species such as cottonwood (Twedt and Portwood 1997). Cottonwood could be harvested twice at ten-year intervals for pulp wood. During the twenty year period of pulp wood production, acorn-producing RPM™ seedlings would increase the potential to naturally regenerate oak in the floodplain and provide wildlife food (mast). After the second pulp wood harvest, RPM™ seedlings and other naturally seeded tree seedlings should be large enough to dominate the reforested tract. Interplanting early-successional species with mast-producing species such as oak and pecan can promote rapid colonization by migrant birds, enhance plant species diversity, promote a more rapid financial return to landowners and enhance the public's perception of reforestation efforts (Twedt and Portwood 1997).

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Estimates of additional Maize (*Zea mays*) yields required to offset costs of tree-windbreaks in Midwestern USA

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Key words: Break-even, Field windbreak, Leeward protected zone, Present value

Abstract

Field windbreaks can increase crop yield within a protected zone. However, they also take land out of crop production and compete with adjacent crops. Although the beneficial aspects are generally recognized, the question arises whether the windbreak will increase crop revenue enough to offset costs over time. Achieving additional yields to offset windbreak costs might be a sufficient incentive for a producer to plant a windbreak. Additional maize (*Zea mays*) yields necessary to break even with costs are calculated for four typical Midwestern USA field windbreaks: poplar (*Populus* spp.), mixed tree/shrubs (*Populus* spp., *Acer saccharinum L./Physocarpus* spp., *Viburnum* spp., *Cornus* spp.), and two and four-row spruce (*Picea* spp.) windbreaks. Five lifespans, two management and two cost scenarios, and three protected zone widths to account for changing sheltering effects are evaluated. Greatest additional yields are for a 4-row spruce windbreak with intensive management at high cost and a 10-year lifespan: 15.38 Mg ha^{-1} yr^{-1} within 6H, 7.69 Mg ha^{-1} yr^{-1} within 12H and 6.15 Mg ha^{-1} yr^{-1} within 15H. If a 50-year lifespan is implemented, the additional yields are about 11% of those in 10-year lifespan. Smallest additional yields are for a mixed tree/shrubs windbreak with extensive management at low cost and a 50-year lifespan: 0.56 Mg ha^{-1} yr^{-1}, 0.28 Mg ha^{-1} yr^{-1} and 0.22 Mg ha^{-1} yr^{-1}, respectively. The mixed windbreak is likely to have actual maize yield increases comparable to the added maize yields required to break even as long as the lifespan is 30 years or longer with a minimum protected zone of 12H.

Introduction

Field windbreaks provide a wide range of benefits including wind speed reduction, soil erosion control, yield increase and biodiversity enhancement (Johnson et al. 1994; Baer 1989). For this reason, windbreaks not only increase crop production on farmland but also improve its sustainability (Brandle et al. 1992). Although windbreak benefits are recognized by producers, they are reluctant to plant windbreaks because of concerns for land taken out of production and diminished crop harvest (Kort 1988). Moreover, as many of the windbreak benefits do not provide obvious direct financial revenues to the producer, they are not accounted for in typical farm analysis and so there is little incentive beyond enhanced crop yields for producers to establish windbreaks. Furthermore, most of windbreak costs are incurred initially, whereas yield benefits are delayed in time. This creates additional discouragement, as a relatively long time period might be needed before recaptured yield benefits will offset windbreak costs.

Many researchers report that windbreaks do provide a significant crop yield increase that could provide incremental revenues enough to offset windbreak costs. Yield increase can be as high as 200% depending on geographical location, weather and distance from windbreak (Kort 1988). Baer (1989) presents increased yields for various crops up to 110%. GAO (1975) describes maize (*Zea mays*) yield increase as high as 19% within the protected zone from two to ten windbreak heights (H). Further, Brandle et al.

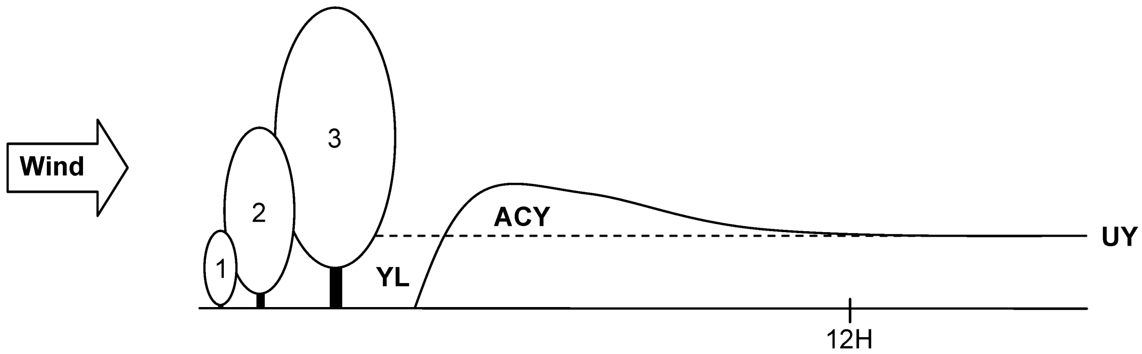

Figure 1. Illustration of yield increase in the leeward protected zone of a windbreak. Vertical scale of yield increase is exaggerated in order to present magnitudes of yield increase and yield loss. Adapted from GAO (1975) and Stoeckeler (1962). 1 – row of shrubs, 2 – row of silver maple, 3 – row of poplar, *YL* – yield loss on the leeward protection zone, *ACY* – additional crop yield on the leeward protection zone and *UY* – unprotected yield.

(1984) provide evidence that wheat (*Triticum aestivum*) yield increase can be as high as 50%. It is necessary to stress that yield increases vary significantly and depend on several factors including weather conditions and windbreak structure that has a direct impact on a wind speed (Brandle et al. 2000; Kort 1988; Brandle et al. 1992; Brandle et al. 1984). Further, yield increase is not uniform across the field; rather it depends on the distance from a windbreak (GAO 1975; McMartin et al. 1974; Stoeckeler 1963).

Economic analyses of yield increase are relatively few and limited to short time periods that do not take into account the entire effective lifespan of a windbreak. Therefore, such analyses may not reveal the full value of the yield increase and associated costs. Nevertheless, studies conducted so far reveal interesting results and give some perspective for future analysis. Brandle et al. (1984) conducted a benefit-cost analysis and used payback period and Net Present Value (NPV) as economic criteria to evaluate a windbreak project. In another study, Brandle et al. (1992) evaluated selected windbreak systems with NPV and various discount rates. Powell (1985) evaluated windbreaks in terms of cost savings. In contrast, McMartin et al. (1974) compared the value of the yield with windbreak protection to the value of the crop with no protection, but over a short time period. Similarly, Stoeckeler (1963) compared yield gain to the base yield of an unprotected field.

Here, we calculate additional maize yields that would allow a maize producer to break even for a given windbreak scenario (defined by windbreak species, lifespan, management intensity and cost option). We assume that to provide sufficient incentive for a producer to plant a windbreak, the expected benefits of additional maize yield must at least equal the costs of establishing and managing the windbreak. Therefore, we calculate additional maize yields that are required to offset costs (to break even) for selected windbreaks and examine if there is evidence in the literature that such yield increases can be achieved. If observed yield increases are greater than those needed to break even, a producer will be able to generate revenue greater than costs and will have a stronger incentive to plant a windbreak. Further, we establish the time needed to attain additional crop yields needed to break even, and examine the influence of protected zone length on these yields.

Materials and methods

Break-even model

In the model, we calculate additional maize yields that are assumed to occur due to the windbreak protection and are required to break even (see Rose 1977 for a similar model applied to woody plantations for biofuels). These yields are obtained within the protected zone on the leeward side of the windbreak (see Figure 1) and are above the regular yield that is obtained if the field is not sheltered by a windbreak. Figure 1 shows that there is yield loss in the area adjacent to the windbreak due to competition (*YL*). Further, one can see that additional crop yield (*ACY*) starts to increase in relatively close proximity to the windbreak, then it reaches its maximum and starts to